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Semiconductor laser based opto-electronics oscillators

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ABSTRACT

We demonstrate the realization of coupled opto-electronic oscillators (COEO) with different semiconductor lasers, including a ring laser, a Fabry-Perot laser, and a colliding pulse mode-locked laser. Each COEO can simultaneously generate short optical pulses and spectrally pure RF signals. With these devices, we obtained optical pulses as short as 6 picoseconds and RF signals as high in frequency as 18 GHz with a spectral purity comparable with a HP8561B synthesizer. These experiments demonstrate that COEOs are promising compact sources for generating low jitter optical pulses and low phase noise RF/millimeter wave signals.

Key words: Opto-electronic oscillator, optical pulse, RF photonics, signal generation, mode-locked lasers, microwave generation, phase noise, jitter.

1. INTRODUCTION

Photonic RF systems[1-3] embed photonic technology into the traditional RF systems. In particular, in a photonic RF system optical waves are used as a carrier to transport RF signals through optical fibers to remote locations. In addition, some of the RF signal processing functions such as signal mixing,[4] antenna beam steering,[5,6] and signal filtering[7,8] can also be accomplished optically. The photonic technology offers the advantages of low loss, light weight, high frequency, high security, remoting capability, and immunity to electromagnetic interference.

Traditional RF oscillators cannot meet all the requirements of photonic RF systems. Because photonic RF systems involve RF signals in both optical and electrical domains, an ideal oscillator for the photonic systems should be able to generate RF signals in both optical and electrical domains. In addition, it should be possible to synchronize or control the oscillator by both electrical and optical references or signals.

Presently, generating a high frequency RF signal in the optical domain is usually done by modulating a diode laser or an external electro-optical (E/O) modulator using a high frequency stable electrical signal from a local oscillator (LO). Such a local oscillator signal is generally obtained by multiplying a low frequency reference, (e.g. quartz oscillator) to the required high frequency, say 32 GHz, with several stages of multipliers and amplifiers. Consequently, the resulting system is bulky, complicated, inefficient, and costly. An alternative way to generate photonic RF carriers is to mix two lasers with different optical frequencies.[9] However, the resulting bandwidth of the signal is wide (limited by the spectral width of the lasers, typically greater than tens of kilohertz) and the frequency stability of the beat signal is poor, caused by the drift of the optical frequency of the two lasers.

We developed a new class of oscillators, Opto-electronic oscillators (OEO)[10,11], for generating high spectral purity, high frequency, and high stability RF signals and optical subcarriers. We have demonstrated an OEO operating at 10 GHz with a phase noise of -140 dBc/Hz, 10 kHz from carrier.[12] This is the lowest phase noise signal from a free running oscillator operating at room temperature.

In previously reported OEOs, the optical oscillation of the pump laser is isolated from the electronic oscillation. In a recent paper,[13] we demonstrated a Coupled Opto-Electronic Oscillator (COEO) in which the laser oscillation is directly coupled with the electronic oscillation. The coupling of the microwave and optical oscillations causes the laser to modelock, generating stable optical pulses and microwave signals simultaneously. Because of its unique features, COEOs will find wide applications in RF communication systems, fiber optic communication systems, and photonic analog-to-digital conversion systems.

In this paper, we present three new configurations of COEO for simultaneously generating low jitter picosecond optical pulses and high spectral purity microwave signals beyond 10 GHz. We will discuss, in particular, two configurations involving integration of the laser and modulator to make compact and cost effective COEOs.

2. RING LASER BASED COEO

In the previously reported COEO,[13] a semiconductor optical amplifier (SOA) is used in a ring configuration to form the optical oscillation loop and the RF oscillation loop directly feeds back to the SOA to modulate its gain. Due to the slow response of the SOA, the RF oscillation frequency is limited to below 1 GHz. To increase the RF oscillation frequency, here we use a Mach-Zenhder modulator in the laser oscillation loop to modulate the loop gain.

The experimental setup of the COEO is shown in Fig. 1a. The output of a semiconductor optical amplifier (SOA) is connected to a Mach-Zehnder modulator of 10 GHz bandwidth. One of the outputs from the modulator is fedback to the SOA via a polarization controller to form a ring laser. The other output port of the modulator is delayed by a 800 meter optical fiber, detected by a photodetector, amplified by an RF amplifier, filtered by an RF bandpass filter centered at 10 GHz, and finally is coupled to the RF modulation port of the modulator to form an opto-electronic feedback loop. Just like an OEO, when the gain of the feedback loop is larger than one, an opto-electronic (O/E) oscillation will start. The opto-electronic feedback loop (about 800 meters) is much longer than the loop length of the ring laser, resulting in a corresponding mode spacing much smaller than the mode spacing of the ring laser, as shown in Fig. 1b and 1d. The center frequency of the RF bandpass filter is chosen such that it is equal to an RF beat frequency of different modes of the ring laser, as shown in Fig. 1c. The bandwidth of the filter is chosen to be narrower than the spacing of the beat frequencies (equivalent to the mode spacing of the ring laser).

Within the pass band, there are many OEO modes competing to oscillate. However, the winner is the mode with a frequency closest to a beat frequency of the laser's longitudinal modes, since only this mode can get energy from the laser, as shown in Fig. 1d. This OEO mode is fed back to modulate the gain of the ring laser and it effectively mode locks the ring laser. The mode locking makes the mode spacing of the laser equal to the frequency of the oscillating OEO mode, which is a multiple of the natural mode spacing of the laser, as shown in Fig. 1e. Because all the oscillating modes in the mode-locked laser are forced in phase, all the mode beat signals between any two neighboring laser modes will add up in phase and generate a strong signal at the frequency of the oscillating OEO mode. This enhanced mode beat signal in turn provides more gain to the oscillating OEO mode and reinforces its oscillation, as shown in Fig. 1f.

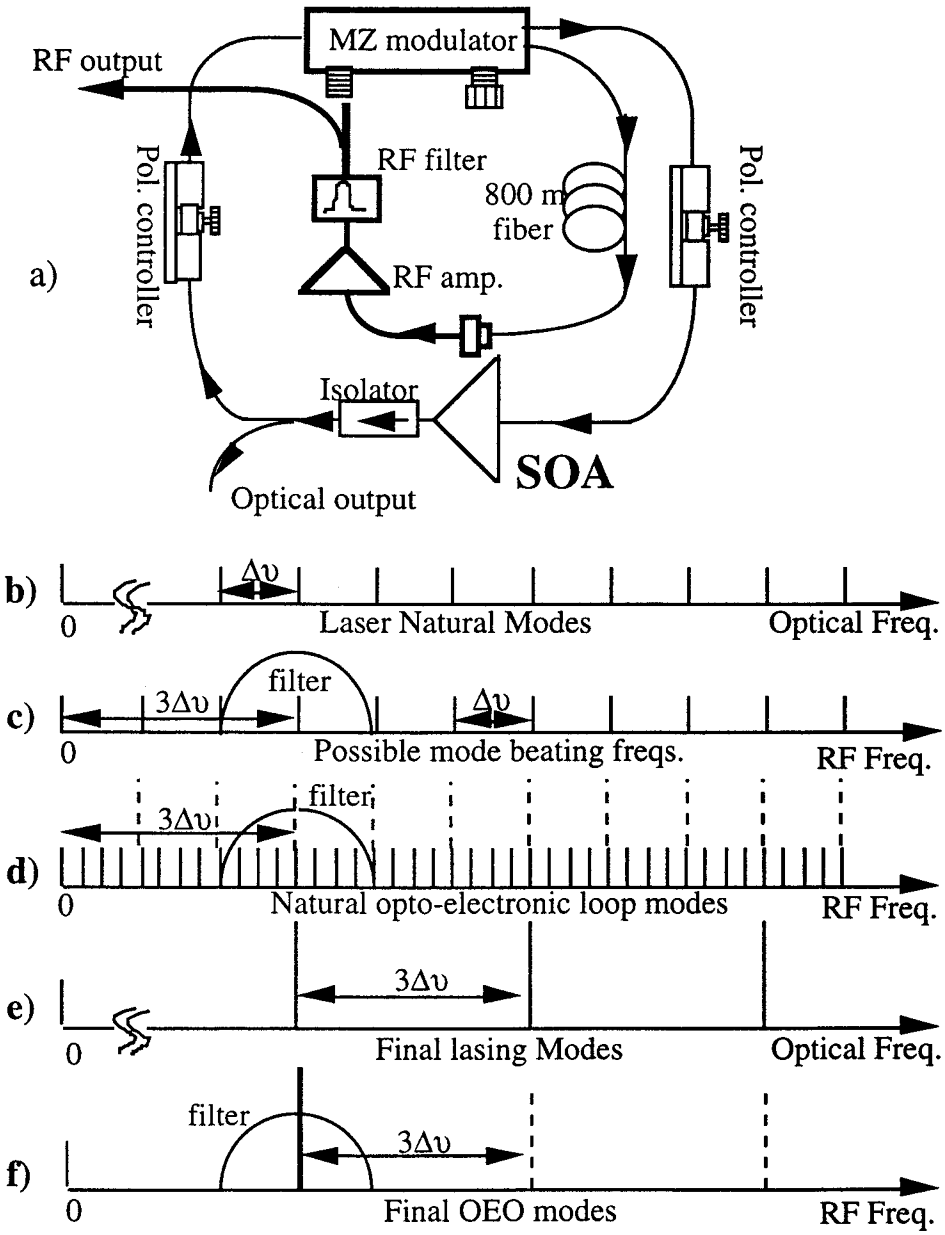

Fig. 1 Fig. 1 a) Illustration of a COEO constructed with a SOA and a Mach-Zehnder modulator. b) All possible laser modes with a mode spacing of Du. They have random phases in the absence of the electro-optic feedback. c) All possible mode beat frequencies of the laser modes in the photodetector. The lowest frequency (Du) corresponds to the sum of the beats between adjacent modes, the second lowest frequency (2Du) corresponds to the sum of the beats between every other modes, and so on. Due to the random phases of the laser modes, these beat signals are weak and noisy. d) All possible oscillating modes defined by the opto-electronic loop. Only those modes aligned with a mode beat frequency can get gain (or energy) from the laser. An electrical filter with a bandwidth narrower than the mode spacing of the laser selects one OEO mode (f = 3Du in the illustration) to oscillate. e) The selected OEO oscillation then drives and mode-locks the laser, limiting the number of oscillating laser modes and forcing them to oscillate in phase. f) The beat of the in-phase laser modes in turn greatly enhances the selected OEO oscillation.

The experimental arrangement is similar to a regeneratively mode-locked laser;[14] however here the O/E oscillation modes, which were not considered in regenerative mode-locking, play a critical role. In particular, the long fiber delay for the opto-electronic loop stores the phase information of both the opto-electrical oscillation and the optical oscillation. The feedback of the stored phase information is the key to high spectral purity oscillations. Similar to a conventional OEO, the phase noise of the O/E oscillation, which directly translates to the jitter of the optical pulses, is expected to be inversely proportional to the time delay squared. Longer O/E loop delay reduces the phase noise of the generated microwave and lowers the jitter of the optical pulses.

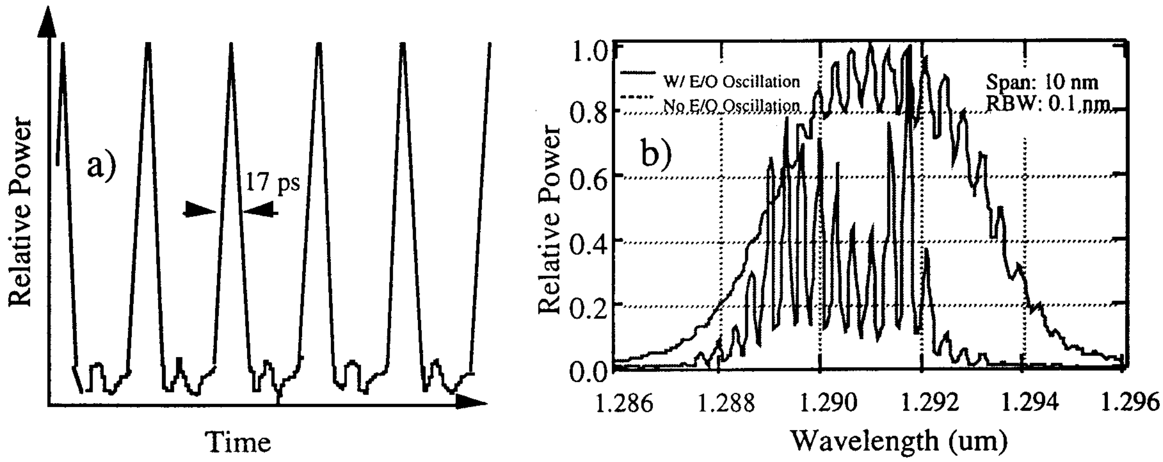

Fig. 2 a) Time domain measurement of the optical pulses. b) Optical spectrum of the ring laser with (upper trace) and without opto-electronic oscillation (lower trace).

The pulses generated by the COEO were measured with a New Focus 40 GHz detector and a Tek CSA803 communication signal analyzer, and the result is shown in Fig. 2a. The measured pulse width is 17 ps, limited by the rise time of the sampling head (SD-26). However, our preliminary autocorrelation measurement indicated a pulse width of 15 ps. On the other hand, the optical spectrum of the pulses, as shown in Fig. 2b, has a bandwidth of 4 nm, implying that the pulses were not transform limited.

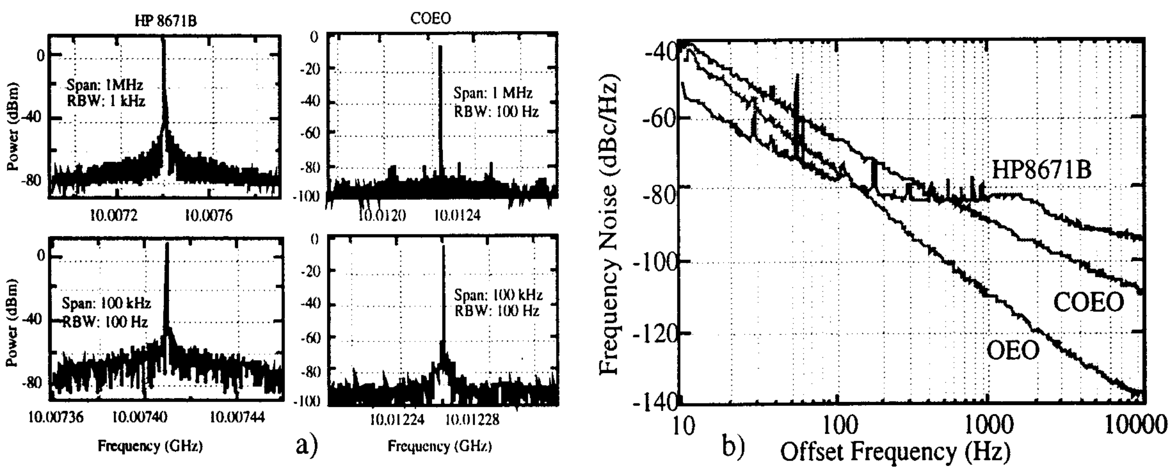

Fig. 2 a) Measured RF spectra of the COEO output at different spectrum analyzer settings and the comparison with a signal from a HP8671B synthesizer. b) Single sideband phase noise comparison of the COEO, an OEO and a HP 8671B synthesizer at 10 GHz.

The measured RF spectrum are compared with a high performance synthesizer (HP8671B), as shown in Fig. 3a. Clearly, for the spectrum analyzer settings, the spectral purity of the COEO is better than that of HP8671B. We also measured the phase noise of the COEO and the result is shown in Fig. 3b. For comparison, the phase noises of HP8671B synthesizer and a conventional OEO with 2 km loop length are also shown in Fig. 3b. It is evident that at 10 kHz from the carrier, the phase noise of the COEO is about 10 dB better that of HP8671B, however, substantially larger than that of the conventional OEO. We expect to further lower the phase noise of the COEO by increasing its loop delay and employing other noise reduction techniques.

3. FABRY-PEROT LASER-BASED COEO

A COEO can also be constructed with Fabry-Perot lasers for reduced size and cost, as shown in Fig. 4. To increase optical power and modulation speed, and reduce the chirp effect, an active gain medium is integrated with an electro-absorption modulator inside the laser cavity. Because electroabsorption modulators with a bandwidth greater than 60 GHz have been demonstrated, such an approach is promising for achieving millimeter wave oscillations.

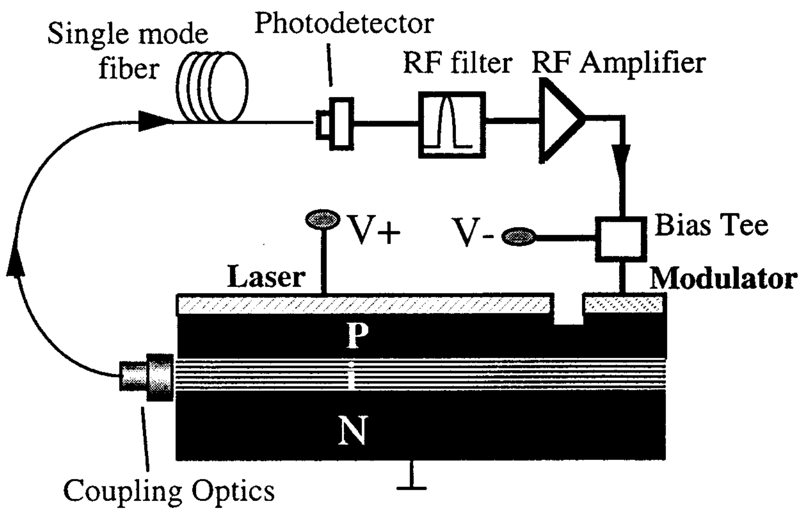

Fig. 4 Illustration of a COEO constructed with a Fabry-Perot laser and an integrated electro-absorption modulator inside the laser cavity.

The integrated laser/modulator uses the identical active layer approach. The active layer of the laser and modulator is made of InGaAsP/InP multiple quantum wells with a graded index InGaAsP cladding. The total length of the integrated laser/modulator is about 3 mm, which gives the Fabry-Perot mode spacing of 15 GHz. The laser and modulator are electrically isolated by an etched groove in between them. The modulator has a length of less than 100 mm. The lasing wavelength is around 1355 nm. When no bias is applied to the modulator section, the laser shows a threshold current of 50 mA. The facet output power from the laser is about 10 mW at a driving current of 150 mA, and 20 mW at driving current of 300 mA. A tapered single mode fiber is used for butt coupling and the coupling efficiency is more than 50%. Fig. 5 shows the laser output power (coupled into a single mode fiber) as a function applied voltage across the modulator. The high output power of this laser is excellent for obtaining OE oscillation.

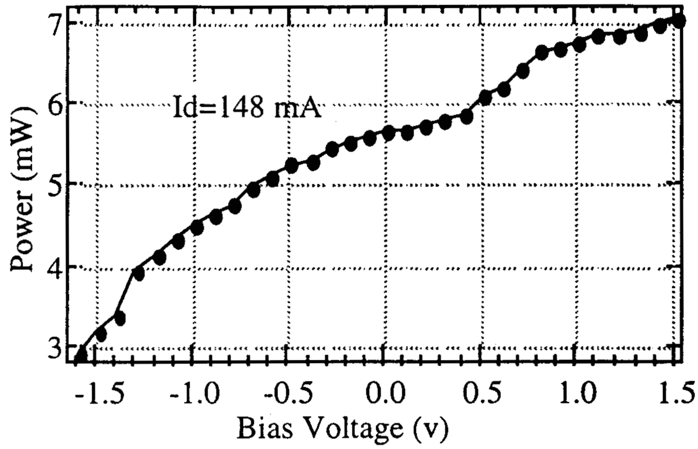

Fig. 5 The laser output power coupled into a single mode fiber as a function of bias voltage across the electro-absorption modulator.

The chip is bonded to a Silicon carrier for RF testing. The RF reflection and modulation response were measured with a HP8607A Lightwave Network Analyzer and are shown in Fig. 6a and 6b. As indicated in Fig. 6a, the modulation response has a sharp peak at 13.6 GHz, due to the resonant enhancement. When closing the OE loop, this resonant enhancement will force the OE oscillation at 13.6 GHz and cause the laser to mode-lock, as explained in the first section. As can be seen, the reflection coefficient of the device is about -15 dB at 10 GHz and -8 dB at 15 Ghz.

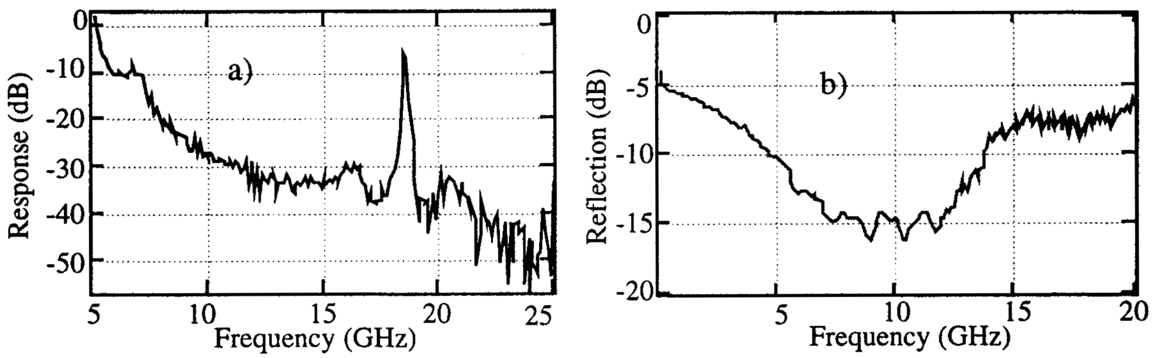

Fig. 6 a) RF response of the integrated laser/modulator. b) RF reflection coefficient of the integrated laser/modulator.

The mode-beating spectrum of a free running laser was observed with a photodetector directly connected to a RF spectrum analyzer and is shown in Fig. 7a. The strong mode beating at 13.6 GHz again indicates that when closing the OE loop, the COEO will be forced to oscillate at 13.6 GHz and cause the laser to mode-lock. The RF spectrum also indicates that the laser is free of self-pulsation under the operating condition.

The phase noise of the mode-beating signal was significantly reduced when a RF signal of 5 dBm at 13.6 GHz was applied to the E/A modulator, as shown in Fig. 7b. This indicates that the laser can easily be mode locked. Unfortunately, due to lacking a key RF component at the time of experiment, we were not be able to close the O/E loop and demonstrate COEO operation using this device.

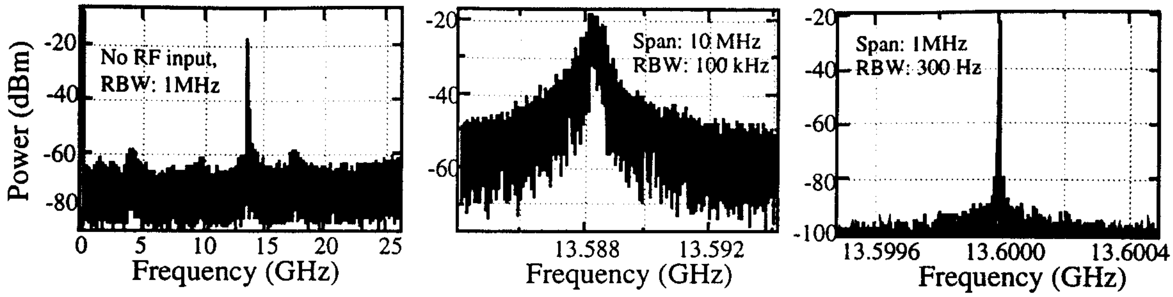

Fig. 7. a) and b) Mode-beating spectrum of a free running integrated laser/modulator for different spectrum analyzer settings. c) The mode beating spectrum of same device with a 5 dBm RF signal at 13.6 Ghz applied to the modulator. Note the difference in total span and resolution bandwidth (RBW) of the spectrum analyzer settings.

4. COEO BASED ON COLLIDING PULSE MODE-LOCKED (CPM) LASERS

Colliding pulse mode-locking has been the most effective technique to generate ultrashort optical pulses in passive mode-locked dye lasers. Y. K. Chen and M. C. Wu[15] successfully demonstrated monolithic integration of a CPM laser on a InP substrate and obtained subpicosecond pulses at repetition frequencies up to 350 GHz. We demonstrate here that by incorporating an electro-optic oscillation loop with a CPM laser, one can greatly reduce the phase noise and frequency jitter of the laser pulses. The effect is similar to that of injection locking the laser with an external RF source, however the external RF source is not needed here and the generated signal quality is not limited by the external signal source. Therefore, such a CPM-based COEO can be used as a stand-alone compact source for both mm-wave signals and subpicosecond optical pulses.

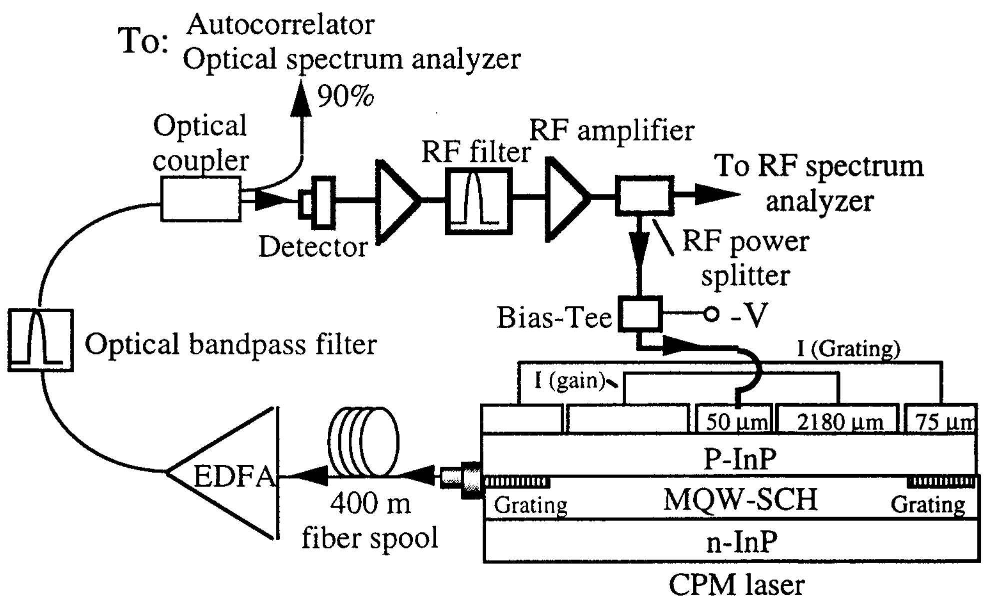

Fig. 8 The cross-section illustration of a colliding pulse mode-locked laser and a COEO constructed with the laser.

The monolithic CPM laser used in this experiment has been cleaved from a multi-wavelength laser array designed for soliton communications[16,17] and is fabricated using two MOCVD growths. The first growth is a separate confinement heterostructure with 4 compressively strained (ε=1%) quantum wells at 1.55 µm and confined on either side by 120 nm of

InGaAsP (λ=1.2 µm). After the diffraction gratings were written by direct write electron beam lithography and etched into the SCH region, the upper cladding and contact layers were grown. The lasers were fabricated into a 3.5 µm wide ridge laser structure with a continuous active region. As seen in Fig. 8, the symmetric 4.6 mm long ridge was divided into 5 sections with 3 contacts: the two end sections are 75 µm each and contain the gratings; the two gain sections are 2180 µm; and a center saturable absorber section of 50 µm. The sections are separated by four 10 µm wide gaps, and electrical isolation of ~ 1kΩ is achieved between the sections by etching the InGaAs contact layer. The fabrication of a microwave ground-signal-ground (GSG) contact for the saturable absorber allows for high frequency probing. A continuous gain region has been employed for ease of fabrication and the elimination of multiple reflections within the cavity.

The threshold current for uniformly pumped devices without gratings is approximately 120 mA. Devices with gratings show thresholds of 135 - 155 mA depending on the lasing wavelength with respect to the gain peak. When a reverse bias is applied to the saturable absorber, the devices exhibit passive mode-locking for a range of gain currents and saturable absorber voltages. Typical operating currents are in the range 165-210 mA and typical saturable absorber voltages are –0.5 to –2.0 volts. The devices mode-lock best near threshold (as seen in [6]), and have facet powers of ~ 1mW at the optimal operating points. Outside the mode-locking regime of operation, the RF spectra shows a distinct peak at both the cavity fundamental of 9.03 GHz and at the mode-locking frequency of 18.06 GHz. Under the proper bias conditions, the device mode-locks at 18.06 GHz with removal of the CW component, and the 9.03 GHz peak is strongly (> 30 dB) suppressed. However, just like other passively mode-locked lasers, the pulse jitter and phase noise are extremely high due to the high spontaneous emission noise of the laser, the complex interaction of the gain-index-carrier density in semiconductors, and insufficient Q of the laser cavity.

One may supply a sinusoidal clock signal at 18.06 GHz to the saturable absorber of the device to reduce the phase noise and jitter. However, this adds cost, size, and power of the device significantly. In addition, the phase noise of the laser will be limited by the external source.

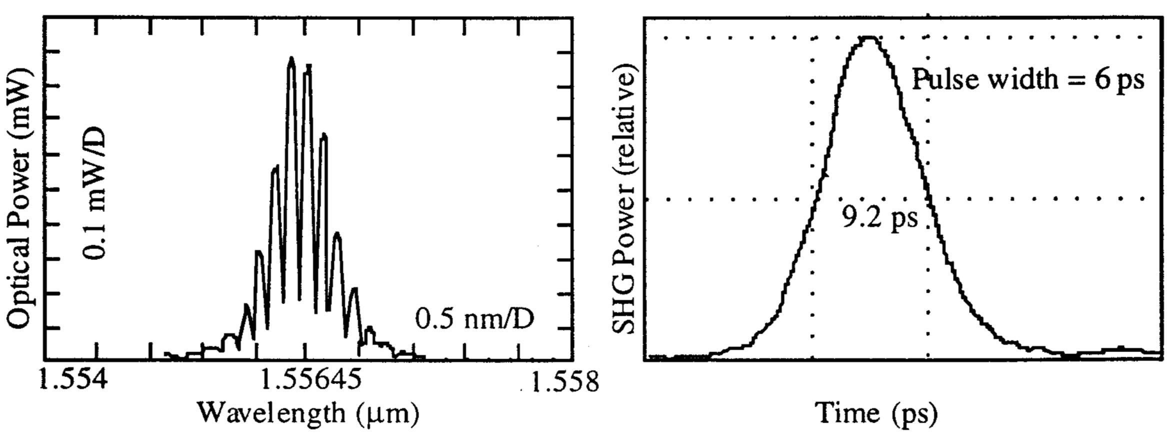

Fig. 9 a) The optical spectrum of a pulse train from a CPM laser based COEO. b) the auto-correlation measurement of the pulse train. Pulse width is 65% of the autocorrelation width if $sech^2$ pulse shape is assumed.

To make a stand alone low noise signal source, we constructed a COEO with the CPM laser, as shown in Fig. 8. The fiber spool has a length of 400 meters, corresponding to a RF Q^{11} of 2.26×10^5 for a 18 GHz signal. Note that the use of EDFA in the loop is not mandatory for the operation of the COEO. It is used merely to boost the optical signal so that the optical pulses can be measured with an autocorrelator. We made the COEO operational even without the insertion of the EDFA in the loop.

After closing the opto-electronic loop, stable mode-locked pulses are immediately present. The spectral and autocorrelation measurements of the optical pulses are shown in Fig. 9a and Fig. 9b respectively. The spectral width $\Delta\lambda$ is about 0.56 nm and the pulse width $\Delta\tau$ is 6 ps if $sech^2$ pulse shape is assumed. The time and bandwidth product is thus 0.42, slightly above transform limit of 0.32.

Stable opto-electronic oscillation was also observed with a RF spectrum analyzer at the RF output port of the COEO, as shown in Fig. 10a and 10b. The mode spacing of the O/E oscillation is about 487 kHz, in consistence with the O/E loop length. The sidemodes suppression is about 21 dB. The single sideband phase noise of the 18 GHz signal can be estimated from the spectrum analyzer measurement to be -104 dBc/Hz at 100 kHz offset and -86 dBc/Hz at 10 kHz offset. The measured RF spectra of the COEO with or without the EDFA in the loop are about the same. Further phase noise reduction can be achieved by increasing the O/E loop length and by further suppressing the sidemodes using the multi-loop technique.

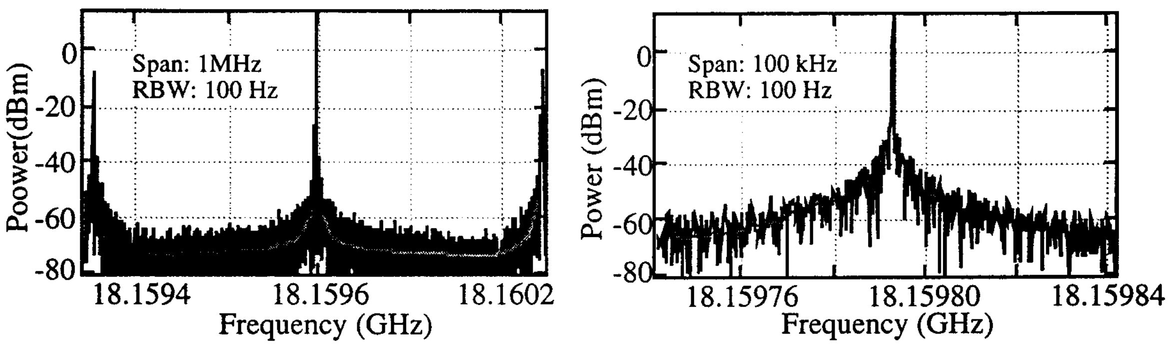

Fig. 10. RF spectrum measurements of a COEO constructed with a CPM laser. Note the different span and resolution bandwidth (RBW) settings of the spectrum analyzer in a) and b).

5. SUMMARY

Three new types of coupled opto-electronic oscillators were investigated experimentally. We generated 17 ps optical pulses and a 10 GHz RF signal with low phase noise using a COEO constructed with an SOA ring laser and a Mach-Zehnder modulator. We also demonstrated the generation of 6 ps optical pulses and a 18 GHz RF signal with a COEO based on colliding pulse mode-locked (CPM) lasers. Finally, we demonstrated that a high power integrated laser/modulator is promising for making a COEO on a chip, greatly reducing the size, power, and cost of the device. The full demonstration of a COEO based on integrated laser/modulator is currently under way. We anticipate that the phase noise and jitter of a COEO will reach those of an OEO (phase noise of -140 dBc/Hz @ 10 kHz away from a 10 GHz carrier) in the near future.

6. ACKNOWLEDGMENT

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